Effects of irrigation withdrawals on streamflows in a karst environment: lower Flint River Basin, Georgia, USA

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Abstract:

Extensive implementation of centre pivot irrigation systems occurred between 1970 and 1980 in the lower Flint River Basin (FRB) of southwestern Georgia, USA. Groundwater within this karstic system is in direct hydraulic connection with regional streams, many of which are incised through the overburden into underlying limestone. We used long-term U.S. Geological Survey gaging station data to evaluate multiple flow metrics of two tributaries (Ichawaynochaway Creek and Spring Creek) in the lower FRB to determine the extent of changes in stream behaviour since irrigation practices intensified. We compared pre- and post-irrigation flow duration curves, 1-, 7-, and 14-day minimum flows, and 8-day (seasonal) and annual baseflow recession slopes, in addition to evaluating regional climate data to determine whether significant differences existed between the pre- and post-irrigation periods. Our results showed significant changes in low-flow durations in the post-irrigation record for both gages, including a decrease by an order of magnitude for 98% exceedance flows at Spring Creek. Both gages indicated significant reductions in 1-, 7-, and 14-day low flows. Eight-day baseflow recession curves (within early summer months) and annual baseflow recession curves became significantly steeper during the post-irrigation period for Ichawaynochaway Creek. We also found that a significant relationship existed between winter and summer minimum flows in both streams in the pre-irrigation period which was disrupted in post-irrigation years. Regional climate data for the study period revealed no significant changes in rainfall totals or frequency of drought; however, there was evidence for a shift in seasonal rainfall patterns. Copyright © 2011 John Wiley & Sons, Ltd.

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INTRODUCTION

The significance of hydrologic connectivity between surface water and groundwater has become an issue of increasing scientific interest and emphasis for over a decade (Stanford and Ward, 1993; Winter *et al.*, 1998; Boulton and Hancock, 2006). Exchange between groundwater and surface water affects both biological and hydrological regimes making the management of groundwater crucial to the protection of surface waters, particularly in regions where groundwater supports baseflow and serves as the major water resource (Shah *et al.*, 2000; Woessner, 2000). Agricultural water use accounts for ∼80% of all the fresh water used worldwide and is inherently consumptive in nature (Postel, 1997). Overextraction of groundwater has been linked to alterations in quantity and quality of surface waters, land subsidence, loss of riparian communities, and damage to the economic health of numerous regions throughout the world (Postel, 1999; Glennon, 2002; Chen *et al.*, 2003; Zektser *et al.*, 2005;

Shi *et al.*, 2007). Intensive groundwater removal near stream channels can cause changes in regional hydrologic gradients resulting in streamflow depletion (Sophocleous, 2002). Lowered streamflow can affect channel morphology (aggradation, pool formation, and habitat complexity), lower assimilative capacity, alter stream temperature, threaten aquatic biota (Golladay *et al.*, 2004), and reduce nutrient loading to downstream communities (Pringle and Triska, 2000; Bunn and Arthington, 2002).

Wen and Chen (2006) found that significant flow depletion in reaches within the Platte and Republican Rivers coincided with increased groundwater withdrawal sites accessing the High Plains Aquifer in western Nebraska, USA. Using 40 years of data from three Australian streams, Brodie *et al.* (2008) revealed increased lag time between rainfall and streamflow response as well as depletions in Q90 in the post-irrigation record of the highly developed Owens River, Victoria. Zume and Tarhule (2008) modelled streamflow depletion from groundwater extraction in a semi-arid alluvial system using visual MODFLOW and showed that baseflow reductions and increased stream leakage accounted for a total of 47% of streamflow depletion within the

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Beaver-North Canadian River system in northwestern Oklahoma, USA.

While our understanding of the interaction between groundwater and surface water in alluvial, volcanic and glacial systems has increased, particularly in arid and semi-arid environments (Stromberg *et al.*, 1996; Van-Looy and Martin, 2005; Poole *et al.*, 2006), the dynamics between surface water and groundwater components within karstic systems, particularly in temperate environments, merits greater investigation. Connectivity within karst catchments is dependent on the interaction of complex fractal flow development, local geohydrologic factors, regional hydraulic gradients, and climate. Karst basins exist worldwide and are common where palaeo-oceanic recession has occurred. Many karst areas occur in coastal regions where population growth is stressing freshwater aquifers and adjoining surface water systems.

During the past several decades, burgeoning population growth and reoccurring drought in the southeastern USA have increased demand on limited water resources and generated regional and interstate conflicts. Efforts at mediation between Georgia, Alabama, and Florida over the partitioning of water resources within the Apalachicola-Chattahoochee-Flint River system have been costly, time consuming, and ultimately unsuccessful (Ruhl, 2005). Water is needed throughout this region to support rapidly growing urban centres, agricultural irrigation, power facilities, industrial, municipal and rural water supplies, and fresh and estuarine ecosystems.

Beginning in the 1970s, centre pivot irrigation systems were installed extensively throughout the lower Flint River Basin (FRB) in SW Georgia to drought-proof crops and improve quantity and quality of yields. Groundwater withdrawals for irrigation increased over 100% in Georgia between 1970 and 1976, mainly due to increased water demand when centre pivot irrigation systems replaced less efficient cable tow systems in the southwestern portion of the state (Pierce *et al.*, 1984). Irrigation in this region allows for the implementation of intensive farming practices including multiple harvests per year. Approximately 80% of the water used for irrigation in the lower FRB is extracted from the Upper Floridan Aquifer, a highly productive carbonate aquifer which underlies most of the Coastal Plain province of the southeastern USA (Hicks *et al.*, 1987). Surface waters throughout the Coastal Plain are connected heterogeneously to the Upper Floridan and interchange between groundwater and surface water components can occur rapidly and frequently through sinkholes, springs, and other dissolution paths (Mosner, 2002; Opsahl *et al.*, 2007).

Long-term monitoring of stream gaging stations by the U.S. Geological Survey (USGS) as well as uninterrupted climate records provide data sets of suitable length to compare stream behaviour in response to changing water use patterns in the lower FRB. The inherent heterogeneities in hydraulic conductivity, hierarchical flow patterns, boundary conditions, and other complex unknowns within karst systems can be interpreted through the flow response of the unit hydrograph (Mangin,

1994). Since basin response remains relatively consistent over time, these hydrographs are also informative for documenting changes in hydrologic conditions occurring within a basin due to natural or anthropogenic influences. The objectives of this study were to describe the degree to which stream flows have been altered in tributaries of the lower FRB since irrigation practices intensified and to determine how water use has affected water availability throughout this basin. We hypothesized that increased irrigation would result in a reduction in low-flow durations and other important low-flow metrics (1-, 7-, and 14-day low flows) in streams in the lower FRB. We further hypothesized that baseflow recession, when considered at the scale of both individual storm and annual averages, would show increasingly rapid depletion as irrigation intensified. Finally, we predicted that a relationship might exist between winter and summer streamflow minima which could be affected by increasing irrigation withdrawals. Because changes in observed flows can be the effect of differences in precipitation patterns, we evaluated the regional climate record to determine if significant shifts in rainfall or drought had occurred over the study period ($\sim$1940–2008). This information is urgently needed to update current surface water and groundwater models and to inform resource policy in this and other basins where management must strike a balance between human water supply and ecological sustainability.

METHODS

Site description

The lower FRB is located southeast of the Fall Line Hills within the Dougherty Plain district of Georgia's Coastal Plain physiographic province (Figure 1). The Fall Line Hills creates the western boundary of the Dougherty Plain and the peak of the Solution Escarpment separates the eastern boundary from the Tifton Upland in Florida. Average slope within this nearly level plain is 2·4 m/km. Geology is dominated by karst, mainly limestone, formations of middle Eocene age and younger overlain by undifferentiated Oligocene and Miocene sediments. An undifferentiated overburden of Quaternary sediments is covered by slightly acidic sandy-loam soils (Hicks *et al.*, 1987). The Ocala Limestone is the main water bearing stratum within the region. This formation thins as it updips and outcrops in a northwesterly direction towards the Fall Line Hills and thickens up to 120 m in a southeasterly direction. Percolation of regional precipitation through acidic soils has been transmitted along fractures and bedding planes into the underlying limestone formation, resulting in mature karst development and a series of unconfined, semi-confined, and confined aquifers in this region. We limit our scope to the Upper Floridan Aquifer which is the source of approximately 80% of the groundwater utilized in the lower FRB (Couch and McDowell, 2006). Transmissivity rates in this aquifer are rapid and can reach approximately $1\cdot4 \times 10^4$ m^2/ day

(Hicks *et al.*, 1987). Direction and extent of water movement depends on regional hydraulic gradients, differences in saturation of stratigraphic units, and water usage. The Upper Floridan is recharged mainly by winter precipitation (December–March) when evapotranspiration rates are low (Torak and Painter, 2006). The lower confining unit of the Upper Floridan is formed by the mostly impervious Lisbon Formation. Streams in the area begin as springs and seeps in the Fall Line Hills and flow in a southeasterly direction across the Dougherty Plain exchanging water heterogeneously with the underlying aquifer through springs, fractures, and porous stream beds (Albertson and Torak, 2002; Mosner, 2002). Where the overburden has eroded, streams are incised directly into underlying limestone formations.

Climate in the lower FRB is hot and humid during summer months with temperatures ranging from 18 to 35 °C and winter temperatures ranging between 2 and 13 °C. Average annual precipitation is 1320 mm [min. 747 mm (in 1954); max. 1960 mm (in 1964)] and is distributed unevenly across the region. Rainfall is generally greatest during the winter and early spring but intense rainfall associated with thundershowers or tropical cyclones may occur during late spring, summer, and early fall (noaa.gov, accessed February 2010). Average warm season pan evaporation rates are approximately 821 mm (Lawrimore and Peterson, 2000) or 60% of average annual precipitation.
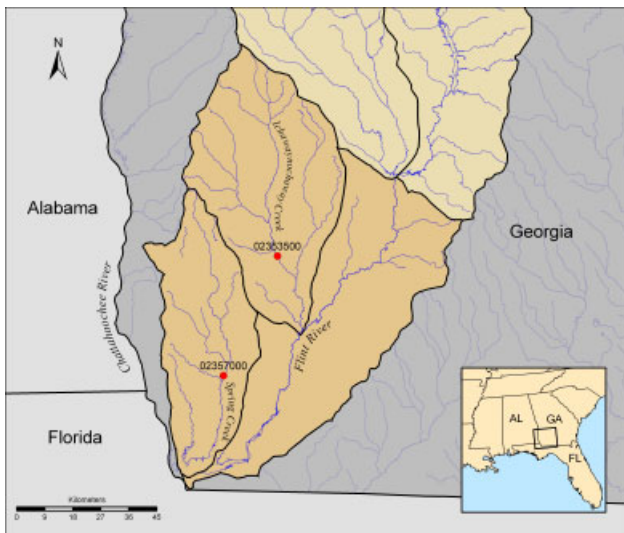

Figure 1. Map of study site: lower Flint River Basin and Ichawaynochaway Creek and Spring Creek sub-basins in southwest Georgia, USA

The study area includes the Ichawaynochaway Creek and Spring Creek sub-basins which lie within the lower FRB (Figure 1). Land use is dominated by agriculture (50%) with remaining acreage in managed forestland and depressional wetlands. Row crop farming of cotton, peanuts, corn, soybeans, and wheat is supported by centre pivot irrigation systems using groundwater sources from the Upper Floridan Aquifer as well as surface water sources. Average irrigation depths for corn, cotton, and peanuts are ~358, 295, and 285 mm/year, respectively (Harrison, 2001). Ichawaynochaway Creek is a fifth-order tributary of the Flint River. Spring Creek, a third-order stream formerly tributary of the Flint, flows directly into Lake Seminole reservoir at the Georgia–Florida border where the Flint and Chattahoochee Rivers join to form the Apalachicola River.

The Ichawaynochaway Creek and Spring Creek sub-basins are the most heavily allocated HUC 8 sub-basins for groundwater and surface water withdrawals within the state (Table I). Presently there are more than 7000 irrigation permits issued to users of >379 m^3/ day in the lower FRB (Couch and McDowell, 2006). Approximately 35·1 m^3/s ($3\cdot03 \times 10^6$ m^3/ day) is permitted in the Ichawaynochaway Creek sub-basin, 66% from surface withdrawals, and the remainder from groundwater (Hook *et al.*, 2005). Removal of 58·7 m^3/s ($5\cdot07 \times 10^6$ m^3/ day) of water is permitted in the Spring Creek sub-basin with 92% coming from the Upper Floridan. Surface water removal includes direct pumping of water from regional streams as well as the diversion of runoff into holding ponds for later application. Groundwater may also be pumped and held in surface ponds for later use.

Low flow duration curves

USGS streamflow records were screened for a minimum of 20 pre- and post-treatment years, leaving only two USGS gaging stations available for analysis: Ichawaynochaway Creek at Milford (Station 02 353 500), in Baker County, GA, and Spring Creek near Iron City (Station 02 357 000), in Decatur County, GA (Table I). Streamflow data sets were divided into pre- and post-irrigation time periods with pre-irrigation for Ichawaynochaway Creek beginning in water year (WY) 1940 (starting 1 October 1939) through WY 1969 (ending 30 September 1969) and post-irrigation period from WY 1980 (1 October 1979) through WY 2008 (30 September 2008). The Spring Creek pre-irrigation period began in WY 1940 through WY 1969 and post-irrigation period was from WY 1983 through WY 2008. The following

Table I. Summary of characteristics of selected sub-basins of lower Flint River Basin taken from summary statistics in USGS Water-Data Reports for 2008

Stream	USGS gage	Years before and after pumping	Average yield (mm)	Basin area (ha)	Irrigated area (ha)	
					Groundwater	Surface
Ichawaynochaway Creek @Milford	02 353 500	30/29	416	160 000	20 632	14 500
Spring Creek near Iron City	02 357 000	30/26	348	125 200	55 434	286

analyses did not include data from most of the 1970s due to temporary interruption of gaging site collection during that decade.

Low-flow duration curves were produced from the record of pre- and post-irrigation daily flows and analyzed graphically for both Ichawaynochaway and Spring Creek (Dunne and Leopold, 1978). Flow duration curves were used to estimate differences in pre- and post-irrigation water yield across the Ichawaynochaway Creek and Spring Creek watersheds for all flows less than the median flow. The differences between the lower end of the pre- and post-irrigation curves (below 50% exceedance flows) were integrated to produce a volume deficit using methods from Davis and McCuen (2005). Each deficit volume was divided by the appropriate HUC 8 watershed area to generate an average depth of lost annual water yield over each sub-basin.

One-, seven-, and 14-day low flows

Changes in average streamflow between the pre- and post-irrigation period were assessed by statistically comparing the distributions of 1-, 7-, and 14-day minimum daily flows for Ichawaynochaway and Spring Creek and graphically evaluating differences in the 7-day low-flow recurrence curves. The lowest 1-, 7-, and 14-day average flows for each WY were calculated from the USGS daily flow records (Ichawaynochaway Creek pre-irrigation: WY 1940–1969, post-irrigation: WY 1980–2008; and Spring Creek pre-irrigation: WY 1940–1969, post-irrigation: WY 1983–2008). Differences in pre- and post-irrigation low-flow metrics were tested using a one-tailed Mann–Whitney nonparametric rank sums test ($\alpha = 0.05$; null hypothesis: pre-irrigation low-flow metrics were equal to post-irrigation low-flow metrics; Zar, 1984; Berryman *et al.*, 1988). Seven-day low-flow duration curves were developed using the Gringorten plot position (Stedinger *et al.*, 1993).

Baseflow recession analysis

A comparison of pre- and post-irrigation baseflow recession behaviour was performed on daily flows from gage data to determine if stream depletion occurred more rapidly in the post-irrigation period (Tallaksen, 1995). Starting on the third day following peak flow, segments of uninterrupted recession which were at least 8 days in length were extracted from the falling limb of all high flow events within the period of interest (Ichawaynochaway Creek pre-irrigation: WY 1940–1969; post-irrigation: WY 1980–2008; Spring Creek pre-irrigation: WY 1940–1969; post-irrigation: WY 1983–2008). From this record, 269 high flow events from the Ichawaynochaway Creek gage and 228 high flow events from the Spring Creek gage fit the recession criteria (excluded extreme flood events of 1994 and 1998). The slope of each storm recession was fit to the following equation:

$$y = b_0 x^{b1} \tag{1}$$

where y equals the estimated flow for x, x equals a given day after the start of the recession, b_0 equals the recession coefficient, and b_1 equals the exponent (slope of the recession). Recession slopes were divided into three seasons: early summer (1 May–15 July), late summer (16 July–31 October), and winter (1 November–30 April) periods and grouped into pre- and post-irrigation years. A *t*-test was used to compare the pre- and post-irrigation median slope for each period ($\alpha = 0.05$). All seasonal data for Ichawaynochaway Creek as well as winter season for Spring Creek failed normality test and data were retested using Mann–Whitney nonparametric rank sum test ($\alpha = 0.05$).

To account for delayed streamflow response due to long-term groundwater extraction, stream data were re-examined for differences in pre- and post-irrigation annual baseflow recession behaviour. Baseflow recession durations of 365 days were extracted from daily streamflow data (Ichawaynochaway Creek pre-irrigation: 1940–1969, post-irrigation: 1980–2007; Spring Creek pre-irrigation: 1938–1969, post-irrigation: 1983–2007) and low points were selected on the receding limb of each annual hydrograph from approximately February to November. Calendar years were used to adequately capture annual recession behaviour. Precipitation events within these recessions that did not result in a rise of greater than 20% over preceding flow points were deleted and recessions were smoothed by extrapolation and fit the following equation:

$$y = b_0 e^{b1x} \tag{2}$$

where y equals the estimated flow for x, x equals a given day after the start of the recession, b_0 equals the recession coefficient, and b_1 equals the exponent (slope of the recession). A one-tailed Mann–Whitney nonparametric rank sums test was executed on pre- and post-irrigation period median slopes ($\alpha = 0.05$).

Winter/summer minimum flow relationships

To determine if a relationship existed between winter and summer minimum flows in streams in the lower FRB, the lowest February daily flow(s) were selected from within each annual recession period and averaged to produce a February mean minimum flow (winter minimum) for each year (Ichawaynochaway Creek pre-irrigation: 1940–1969, post-irrigation: 1980–2007; Spring Creek pre-irrigation: 1938–1969, post-irrigation: 1983–2007). The single lowest minimum daily flow in August was selected from each year to represent the August minimum flow (summer minimum). Note: One to four baseflow points were selected during February, when available, to address the monthly variation within baseflow due to winter recharge during this month, whereas an August minimum baseflow was distinguishable as the single lowest flow on the annual recession during that month. Linear regressions were executed on February *versus* August minima for pre- and post-irrigation years and graphed on a semi-log scatter plot (Zar, 1984).

Climate analysis

The distribution of seasonal climate data from the National Climate Data Center (http://www.ncdc.noaa. gov/oa/ncdc.html, accessed August 2009) was examined over the period of study (1940–2008) to determine if changes had occurred in rainfall patterns between pre- and post-irrigation years (pre = 1940–1974; post = 1975–2008). A Mann–Whitney nonparametric rank sums test ($\alpha = 0.05$) was executed on annual, as well as seasonal, precipitation data for pre- and post-irrigation periods. The Palmer Drought Severity Index (PDSI) was used to identify and compare periods of rainfall deficit (deficits of several months or more) over the period of record to determine if changes had occurred in frequency, severity, or duration of drought since irrigation intensified in the lower FRB.

RESULTS

Low flow durations

Flow duration analysis of these streams indicated substantial reductions in low flows in the post-irrigation

period. For flows exceeding the median flow (50 percentile), post-irrigation flow duration curves for Ichawaynochaway Creek and Spring Creek (Figure 2) were very similar to the pre-irrigation record; however, flows less than the 50% exceedance were much lower in the post-irrigation period. At the 98% exceedance flow, post-irrigation flows were 1/10th pre-irrigation flows, and in Spring Creek, flows fell to zero at the 99% exceedance level. Changes in water yield for all flows less than the median flow from Ichawaynochaway and Spring Creek sub-basins were 38 and 7 mm annually.

One-, seven-, and 14-day low flows

One-, seven-, and 14-day low flows were reduced substantially in the post-irrigation period (Figure 3, all p values < 0.001) for both gages. During this post-irrigation period, median 7-day low flows for Spring Creek and Ichawaynochaway Creek were 51 and 61%, of their pre-irrigation values, respectively (Table II). Relative deviations of the 7-day low-flow recurrence curves for both Spring Creek and Ichawaynochaway Creek increased with increasing average recurrence interval, indicating that effects of pumping were more severe during droughts. In the range of the 10- to 100-year recurrence interval, 7-day low flows were an order of
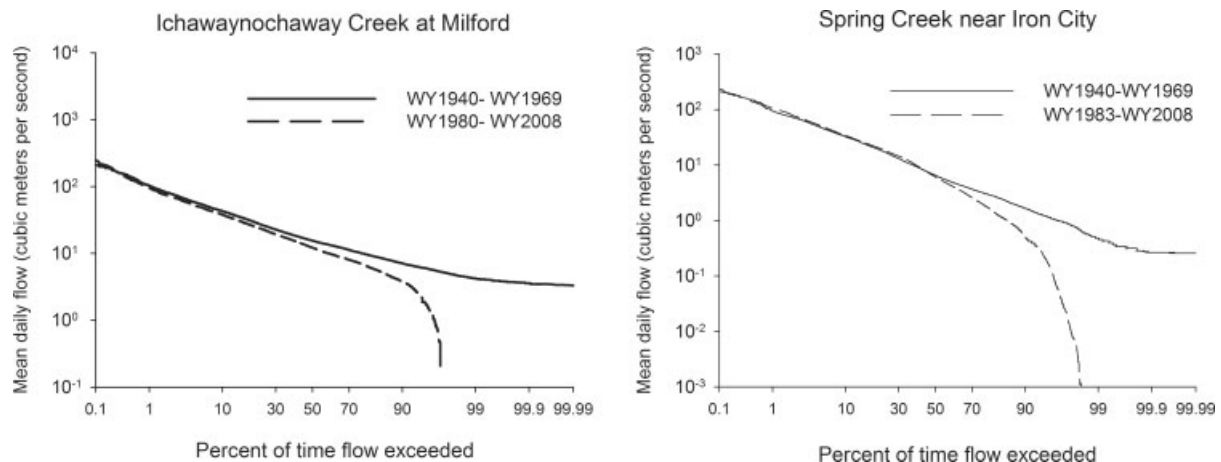

Figure 2. Flow duration curves for the pre- and post-pumping irrigation periods for Ichawaynochaway Creek and Spring Creek, GA
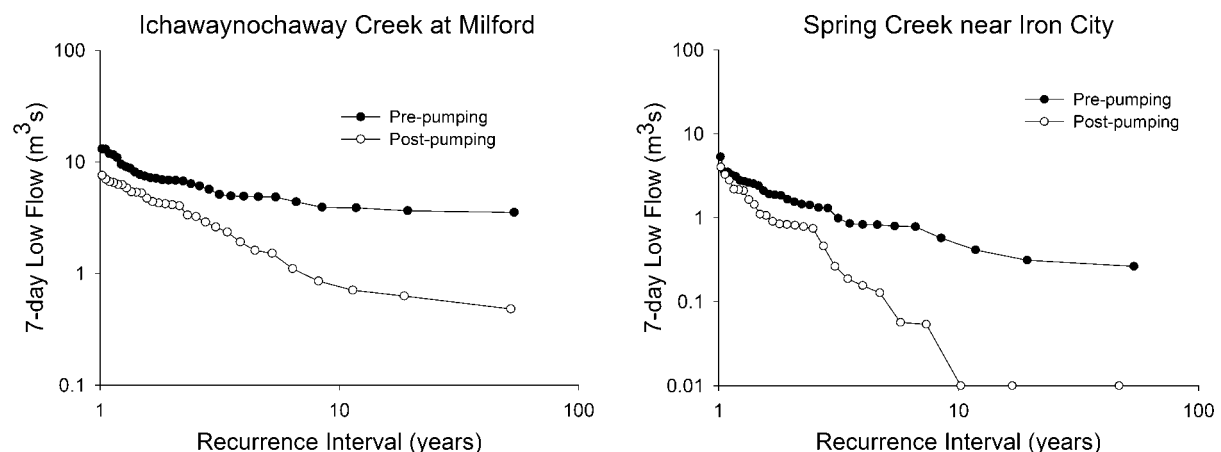

Figure 3. Seven-day low-flow recurrence curves in the pre- and post-pumping irrigation periods for Ichawaynochaway Creek and Spring Creek, GA

Table II. Comparison of highest, lowest, median, mean, and standard deviation of 1-, 7-, and 14-day low flows for the pre- and post-pumping periods[a]

	Ichawaynochaway Creek		Spring Creek	
	Pre-pumping ($N = 30$)	Post-pumping ($N = 29$)	Pre-pumping ($N = 30$)	Post-pumping ($N = 26$)
One-day low flows (m³/s)				
Range (hi-lo)	12·7–3·32	6·96–0·19	4·88–0·26	3·60–0
Median	6·25	3·51	1·42	0·78
Mean	6·73	5·18	1·74	1·01
St. dev.	2·66	2·04	1·11	1·02
Seven-day low flows (m³/s)				
Range (hi-lo)	13·1–3·53	7·57–0·48	5·33–0·26	4·02–0
Median	6·85	4·18	1·60	0·82
Mean	7·17	5·62	1·83	1·08
St. dev.	2·76	2·11	1·17	1·10
Fourteen-day low flows (m³/s)				
Range (hi-lo)	14·2–3·62	8·28–0·63	5·46–0·27	4·60–0
Median	7·37	5·10	1·65	0·90
Mean	7·75	6·21	1·91	1·17
St. dev.	3·02	2·23	1·22	1·19

[a] Differences in pre- and post-pumping 1-, 7-, and 14-day low-flow distributions were tested using a one-tailed Mann–Whitney nonparametric rank sums test (null hypothesis: pre-pumping low-flow metrics were less than or equal to post-pumping low-flow metrics). Differences were significant for all metrics for all gage records (all p values < 0·001).
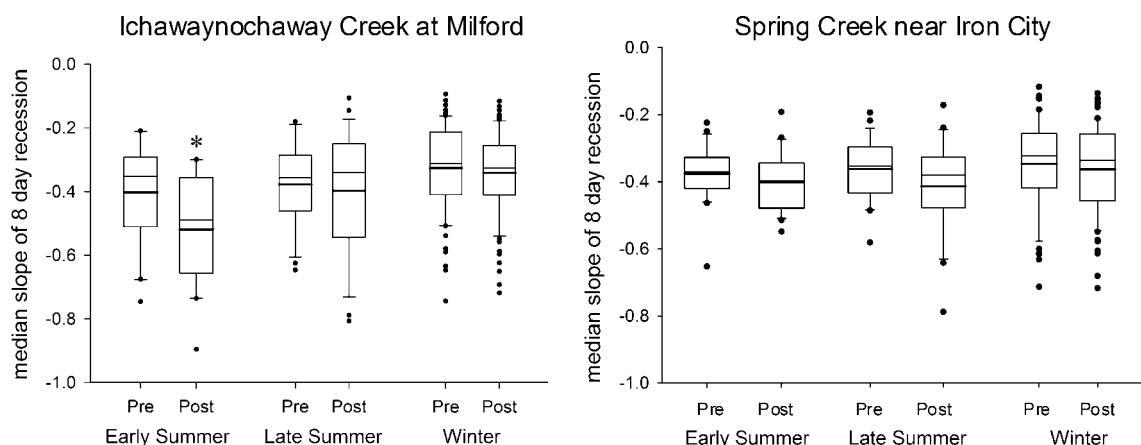

Figure 4. Analysis of median 8-day recession baseflow slopes for Ichawaynochaway Creek and Spring Creek, GA

magnitude lower in the post-irrigation period for both streams. When considering absolute changes, the 7-day low-flow recurrence curve for Ichawaynochaway Creek dropped an almost uniform 3·0–3·5 m³/s in the post-irrigation period. This shift is approximately equal to the 25-year 7-day low flow in the pre-irrigation period.

Baseflow recession analysis

Median 8-day baseflow recession curves were significantly steeper within the post-irrigation record during the early summer period for Ichawaynochaway Creek (Figure 4, p < 0·031). No significant differences were detected for late summer or winter season median slopes on Ichawaynochaway ($p = 0·992$ and 0·436, respectively). There were no significant differences between pre- and post-irrigation median 8-day recession slopes for any season on Spring Creek [$p = 0·366$ (early summer), $p = 0·145$ (late summer), $p = 0·488$ (winter)], but there was a trend towards steeper recessions in the

early summer and late summer seasons. Evaluation of annual baseflow recession curves revealed significant changes in annual recession slopes (steeper) in the post-irrigation period for Ichawaynochaway Creek (Figure 5, p < 0·001). No significant differences between pre- and post-irrigation annual recession slopes were indicated for Spring Creek ($p = 0·174$), although the distribution moved towards steeper recession slopes.

Winter/summer flow relationships

A significant positive relationship was found between winter and summer minimum flows in the pre-irrigation period for both Ichawaynochaway Creek and Spring Creek (Figure 6, both analyses, p < 0·001). In the pre-irrigation period February minimum flows, which were high from recharge between late fall and early winter months, resulted in August minimum flows that were comparatively elevated. However, in the post-irrigation period, February and August minimum flows showed no
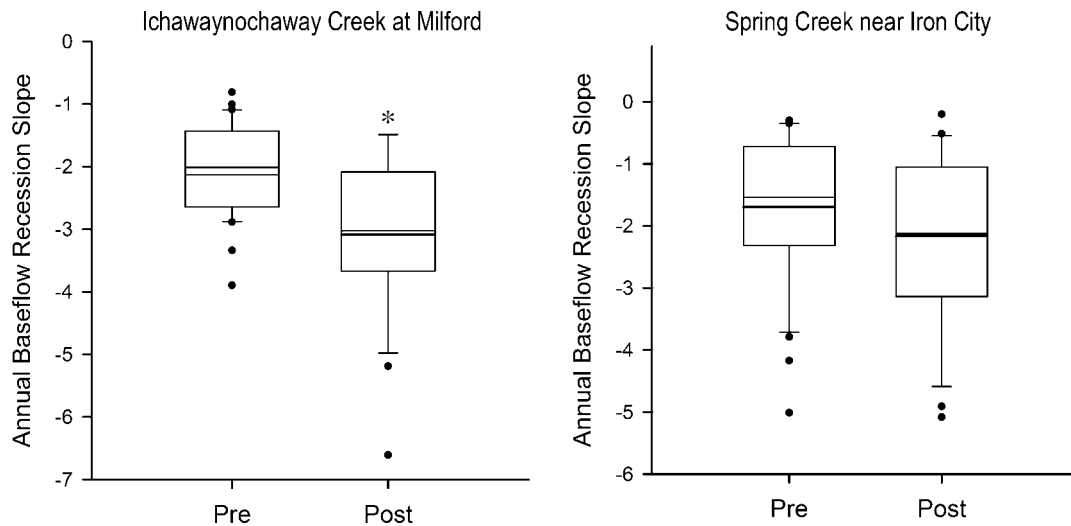
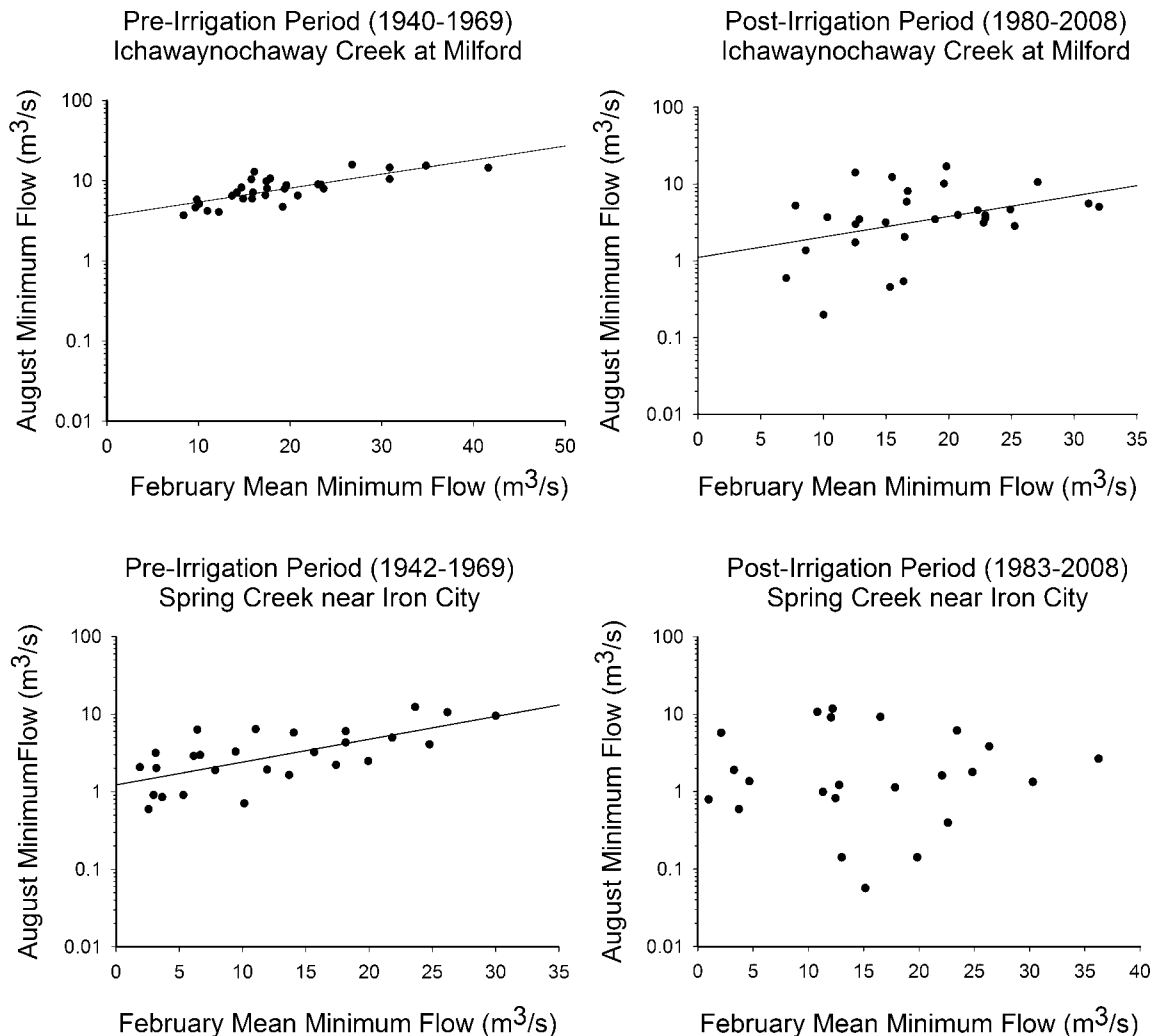Figure 5. Analysis of annual recession baseflow slopes for Ichawaynochaway Creek and Spring Creek, GA

Figure 6. Relationship between winter–summer low flows during pre- and post-irrigation period for Ichawaynochaway Creek and Spring Creek, GA

significant relationship in Ichawaynochaway or Spring Creek indicating that the relationship which had existed between winter and summer minima has been disrupted and minimum winter flows no longer serves as a predictor for upcoming summer minimum flows.

Climate analysis

No significant differences were observed between pre-irrigation (1940–1974) and post-irrigation (1975–2008) precipitation patterns (Figure 7, $p > 0.05$). Both medians
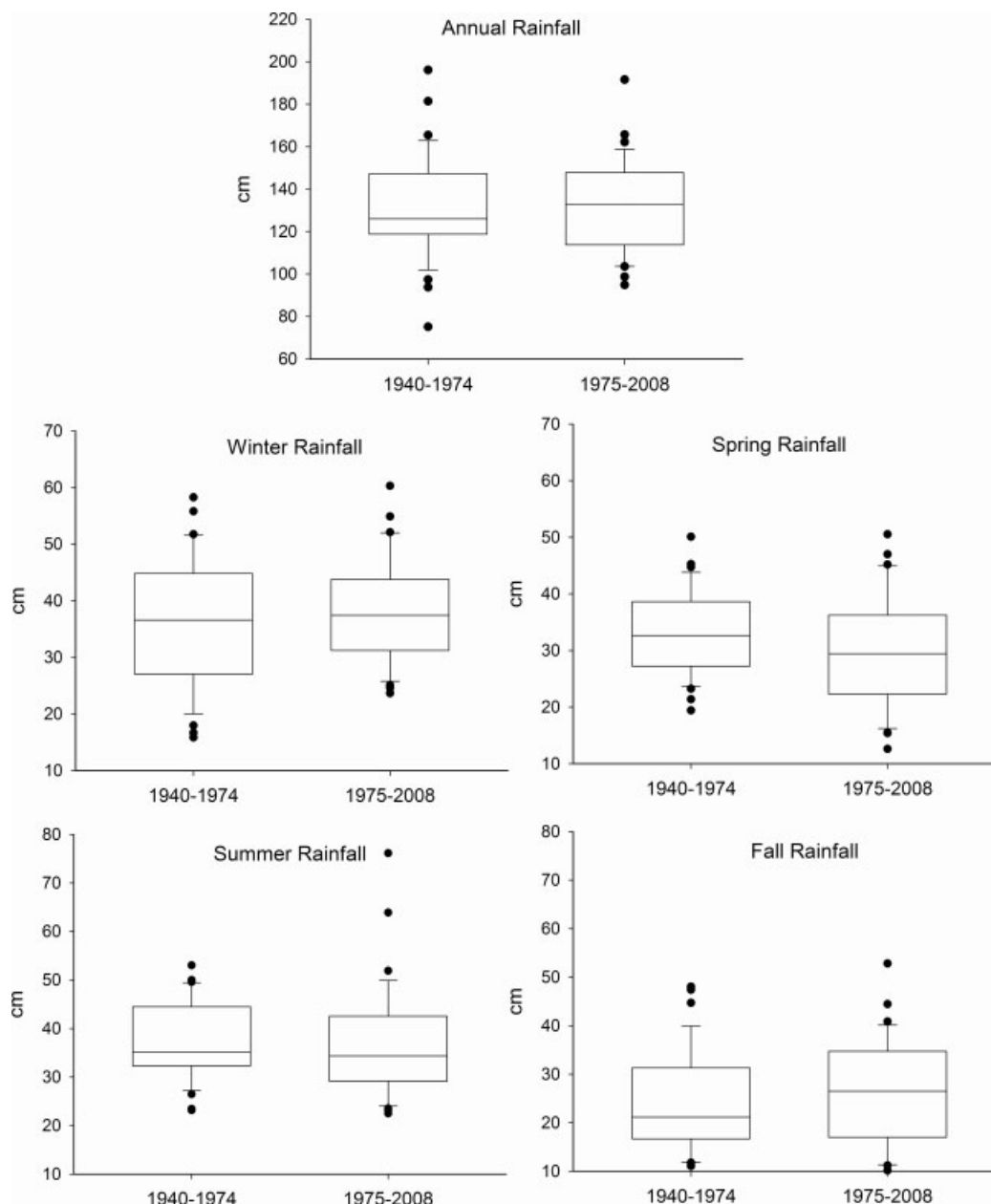
Figure 7. Annual and seasonal precipitation trends for lower Flint River Basin in southwest Georgia for period of record

and mean values suggested that annual, winter, and fall rainfall were slightly greater from 1975 to 2008 (Table III). Spring and summer rainfall tended to be slightly lower. Spring rainfall totals did not pass the equality of variance test (Kolmogorov–Smirnov test $p < 0.05$) suggesting that the two data periods had different distributions. Summer and fall data both failed the normality test (Shapiro–Wilkoxon test $p < 0.05$) suggesting that one or both data sets were non-normal in distribution. Based on these outcomes, the distribution of seasonal data was re-examined to see if subtle changes could be observed over the period of study. Spring rainfall totals showed greater Kurtosis for 1975–2008 supporting the previous test indicating inequality of variance (Figure 7). The PDSI revealed 28 periods of rainfall deficits of several months or more, 8 of which were significant droughts (deficits persisting for greater

than 1 year or exceeding a severity index of −3). These findings revealed an average inter-drought interval of 8·5 years, with four droughts prior to 1974 and four droughts after intensive pumping began (Figure 8), indicating no difference in frequency of drought between the pre- and post-irrigation period.

DISCUSSION

Intensification of agricultural irrigation in the lower FRB has resulted in significant baseflow declines evident in reductions in low-flow durations and 1-, 7-, and 14-day minimum flows in the post-irrigation record for both Ichawaynochaway and Spring Creeks. These declines have been large, making the previous 25-year 7-day low flow in Ichawaynochaway Creek into the 2-year 7-day

Table III. Regional rainfall summary for southwestern Georgia from 1940 to 2008; data are from the National Climate Data Center drought database, accessed August 2009

Period	Annual (cm)	Winter (cm)	Spring (cm)	Summer (cm)	Fall (cm)
Medians and inter-quartile ranges					
1940–1974	126·0	36·6	32·6	35·1	21·2
	118·8–147·3	27·0–44·8	27·2–38·6	32·3–44·5	16·7–31·3
1975–2008	132·8	37·4	29·4	34·4	26·5
	113·8–147·8	31·2–43·8	22·3–36·2	29·1–42·5	17·0–34·7
Means and standard deviations					
1940–1974	131·0 (23·8)	36·7 (11·1)	33·0 (7·4)	37·6 (7·8)	23·7 (10·2)
1975–2008	131·5 (22·0)	38·6 (9·4)	30·0 (10·0)	36·8 (11·4)	26·1 (10·7)

low flow. Spring Creek, a much smaller stream than Ichawaynochaway Creek, was formerly perennial but became intermittent in the post-irrigation period. Large declines in low flows have occurred, while annual water budgets of these streams have changed relatively little. Water level time series in USGS long-term monitoring wells in the area show large and steep summer drops in head, but they do not show trends in winter groundwater levels. On an annual basis, recharge to the system is sufficient to maintain groundwater levels and sustain agricultural irrigation, and this likely explains the small effect of pumping on annual water budgets.

Significant changes in both 8-day early summer and annual baseflow recession curves for Ichawaynochaway Creek indicate that more rapid stream depletion has occurred during post-irrigation years. Effects seen on early summer baseflow recessions in the post-irrigation period correspond to heaviest seasonal irrigation application in this region (April through June). The lack of statistical significance in the Spring Creek annual recession changes may be due to a more constrained streamflow reduction that could occur (i.e. measured flows could not go below zero).

The relatively strong linear relationship that existed between winter and summer minimum flows prior to implementation of extensive irrigation was disrupted in the post-irrigation period in both Ichawaynochaway

and Spring Creek. In pre-irrigation years, high February baseflows would have preceded correspondingly high August baseflows, and low February flows led to low August minima, indicating a persistent effect of winter groundwater levels on subsequent summer baseflows. The lack of correlation between winter baseflows and summer low flows in the post-pumping period indicates that agricultural groundwater pumping has significantly altered groundwater–streamflow relationships. The previous relationship between summer and winter minimum flows could have served as an indicator of impending low-flow conditions and might have been a useful tool for resource managers in charge of protecting stressed water resources, but now February low flows have little value for predicting late summer flow conditions.

Critical habitat is currently designated in streams in the lower regions of the FBR to protect seven species of mussels listed (as endangered or threatened) by the U.S. Fish and Wildlife Service (USFWS). Results of USGS hydrologic modelling of various agricultural pumping scenarios suggest that eight reaches in this area, including Spring Creek and multiple tributaries of the Flint River, are highly sensitive to drying, posing a risk to mussel populations in those reaches (Albertson and Torak, 2002). A severe drought occurring between 1999 and 2001 induced fish and mussel kills in this area and raised concerns over the effects of irrigation withdrawals on streams and dependent biota. The passage of the Flint River Drought Protection Act in 2000 placed a temporary moratorium on irrigation permitting and allowed the Georgia Environmental Protection Agency to buy back limited irrigation rights during drought years to reduce demand on strained regional water resources (Couch and McDowell, 2006). Declaration of drought and announcement of irrigation water buy-back must be declared by 1 March, approximately five to eights months before the lowest flows may be observed in these streams. This regulatory system raised questions on whether winter baseflow conditions might be predictive of upcoming summer low-flow conditions, motivating part of the analysis included in this study.

While groundwater withdrawals are estimated on an annual basis they are generally applied within only a 4- to 6-month period when temperatures and evapotranspiration rates are high. The differences in pre- and post-irrigation water yield for the Ichawaynochaway and
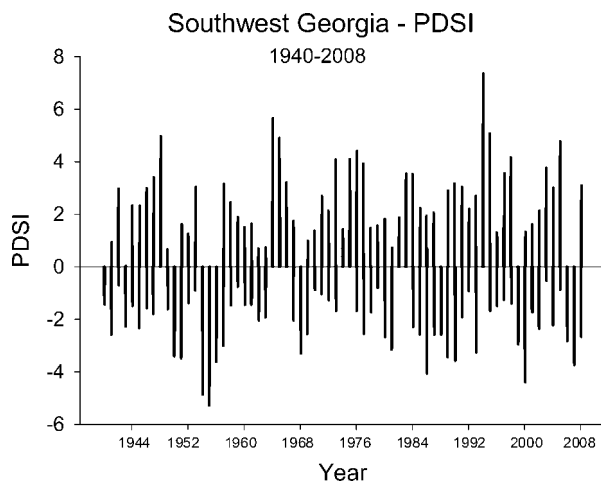

Figure 8. Palmer Hydrologic Drought Index time series for lower Flint River Basin in southwest Georgia for period of record

Spring Creek sub-basins for all flows less than the median flow were 38 and 7 mm/year, respectively. While this amounts to only 4·5 and 0·7% of average annual yield, respectively, it belies the large effects of seasonal irrigation on growing season flows in these basins. When compared with pre-irrigation summer mean flow, these losses represent 12 and 18% of average summer yields for Ichawaynochaway and Spring Creek, respectively. The discrepancy between the small changes to the annual water budget and large changes to the low end of the flow duration curve is explained by the fact that the flow duration curves only diverge for the lower 10% of flows, and this volume of flow is small compared with the annual and seasonal volumes. Spring Creek, the smaller of the two basins, has greater absolute permitted groundwater withdrawals compared to Ichawaynochaway Creek; therefore, it is reasonable that groundwater pumping effects on streamflows would be greater in the Spring Creek sub-basin. The higher percentage of surface water use (directly from stream) within the Ichawaynochaway sub-basin is reflected in the significant alterations to baseflow recession behaviour in early summer months.

Peak irrigation pumping in the lower FRB coincides with periods of generally low summer flows, exacerbating low-flow conditions such as increased stream temperatures and lowered dissolved oxygen levels (Gagnon *et al.*, 2004). Anoxic conditions have been shown to threaten aquatic species in these and adjacent waters. Following severe drought between 1998 and 2000, Golladay *et al.* (2004) reported significant declines in mussel taxa richness and species abundance within mid-stream reaches of Spring Creek, >50% reduction in total mussel abundance, and lowered or absent populations of species of special concern in no-flow reaches. Mussels have been shown to provide valuable ecosystem services by significantly altering nutrient processing and biodeposition in freshwater ecosystems (Howard and Cuffey, 2006; Spooner and Vaughn, 2006). In addition to aiding in the translocation of important nutrients and water clarification within their habitat, these organisms also provide food for a variety of regional fauna including muskrat, otter, raccoons, birds, and fish (Strayer, 2008). Gulf Striped Bass, an important recreational fish in the lower FRB, are also known to seek out spring conduits in regional streams during summer months, seeking relief provided by cooler groundwater inputs. Overcrowding in or lack of access to these important thermal refugia have been shown to increase stress-induced pathology and mortality of adult striped bass (Zale *et al.*, 1990).

Although repeated droughts have occurred in the last decade, our results show there has been no significant reduction in average precipitation or increase in recurrence or severity of drought during post-irrigation years, indicating that lowered flows in this region are not a result of altered climate patterns; however, shifts in distribution of spring and summer rainfall patterns since the 1970s may have created the need for more irrigation. Rose (2009) showed no statistically significant differences in rainfall amounts from 1938 to 2005 in

southeastern USA, including the Coastal Plain region. Seager *et al.* (2009) compared recent southeastern USA drought years (2005–2006) with previous climatic patterns (1856–2004). They concluded that this recent drought was typical relative to historic droughts and suggested current water shortages are due mainly to increasing water demand in this region.

Intensive groundwater removal in the lower FRB has also been shown to have out-of-basin effects. Outside the recharge area, groundwater levels are showing a permanent decline with consumptive water use. Current studies suggest that withdrawal of groundwater resources in the lower FRB has resulted in changes in the potentiometric surface of groundwater in the neighbouring Ochlockonee River Basin due to removal of potential recharge (Jones and Torak, 2006). Following the implementation of intensive irrigation in the 1970s, Stamey (1996) reported reduced inputs to and outputs from Lake Seminole, a man-made impoundment at the confluence of the Flint and Chattahoochee Rivers. Downstream ecosystems and fishing, shrimping and shellfish industries in the Apalachicola Bay, Florida, depend on upstream inputs of fresh water from the lower FRB to maintain adequate levels of nutrients and salinity as well as flushing flows vital to estuarine and marine function (Elder and Cairnes, 1982; Gillanders and Kingsford, 2002).

Current resource policy does not require reporting of water consumption by permitted agricultural irrigators, although many farmers are voluntarily submitting to monitoring programs in this region. While irrigators who applied for permits after 1 July 1988 must comply with protection of established 7Q10 for their watershed, wells which were already pumping >379 m³/ day prior to 1 July 1988 have been 'grandfathered' into the current mandated permitting program and extraction may proceed at original pumping capacity. Groundwater removal of <379 m³/ day requires no permit or monitoring. Agricultural irrigation permits cannot be withdrawn once they have been granted (unless they have not been completed within a year); however, the EPD may suspend pumping during periods of declared drought. If left unchecked, human decisions regarding crop production and extensive irrigation from groundwater resources are likely to continue to significantly affect the availability of surface water resources within the lower FRB as well as downstream.

CONCLUSIONS

Water extraction from the Upper Floridan Aquifer within the Dougherty Plain of southwestern Georgia has substantially reduced stream baseflow in the lower FRB. Because the underlying karstic aquifer is shallow and streams are heterogeneously incised directly into limestone formations, there is a dynamic hydraulic connection between surface water and groundwater resources in this region. The effects of groundwater removal have intensified extreme low-flow and no-flow periods during the

growing season in historically perennial streams. Low flows and resulting hypoxic conditions stress important aquatic biota, including multiple threatened and endangered species. Human population in the southeastern USA is on a trajectory of rapid growth, increasing the need for reliable water resources. In addition, this region is projected to experience more extreme climatic events (including drought) under global climate change scenarios (Easterling *et al.*, 2000). While commodity pricing and loan structuring make it necessary for farmers to use irrigation to compete in current markets, it is essential that future water resource policy be carefully designed in this and other regions where natural and anthropological pressures will continue to stress limited water resources which must be shared between human and ecological communities.

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